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# In-Mine Evaluation of Underground Fire and Smoke Detectors

By Russell E. Griffin

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNITED STATES DEPARTMENT OF THE INTERIOR
Cecil D. Andrus, Secretary

BUREAU OF MINES
Lindsay D. Norman, Acting Director

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# IN-MINE EVALUATION OF UNDERGROUND FIRE AND SMOKE DETECTORS

by

Russell E. Griffin [1]

## ABSTRACT

The current state-of-the-art of fire and smoke detection technology is reviewed from the standpoint of suitability for use in underground metal and nonmetal mines. Detection modes, fire signatures, and environmental considerations are included. Preliminary results of long-term in-mine tests are presented.

## INTRODUCTION

Underground mines are becoming deeper, more spread out, and more mechanized leading to increased combustibles loading, and restricted miner egress. Welding, torch cutting, and electrical shorts account for over 50 pct of fires in noncoal mines since 1945. Spontaneous combustion is another common cause of fires in mines and, as ventilation systems become more complex, this hazard will probably increase. The Bureau of Mines activities and programs in health and safety have addressed this problem and found one of the key needs is reliable sensors for early smoke and fire warning. This report describes sensor characteristics needed to provide rapid and reliable response to fire and smoke, the need for minimizing false alarms along with providing maximum reliability and low maintenance. Bureau experiences with sensor applicability and use in underground mine environments are also described.

Classification of the various smoke and fire sensors into three categories--optical view field, direct contact, and products of combustion (POC)--requires some explanation since most off-the-shelf devices (systems) have more than one principle of response and may respond to more than one parameter. Because hybrid sensors may include heat detectors as well as photoelectric and/or ionization-type POC detectors, classification is according to the primary intended use. For the nonconventional fire detectors that have been developed for gas analysis and detection, the classification may be less obvious. Most of the nonconventional detectors are described in this report under POC types of sensors, even though they may depend on optical- or filament-type principles. A further distinction of detector types divides them into point (or local) source, as opposed to the extended area-type sensor.

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[1] Electronics engineer, Twin Cities Research Center, Bureau of Mines, Twin Cities, Minn.

For more detailed information on the types of fire detectors available, there are good survey articles (9, 14),[2] National Fire Protection Association (NFPA) reference books (10), and manufacturers' sales literature.

## FIRE SIGNATURES

Any product of a fire that changes the ambient conditions is called a fire signature (9), and is potentially useful for detection. To be practical for detection, a fire signature must cause a measureable change in some ambient condition. With other factors being equal, such as hardware costs and detection times versus hazard level, the preferred fire signature is one that generates the highest signal-to-noise ratio in the earliest period of the fire development. The principal fire signatures used in the detectors discussed herein are aerosol, energy release, and gas signatures.

### Aerosols

Aerosols are particles suspended in air. The process of combustion releases large quantities of solid and liquid particles into the atmosphere ranging in size from $5 \times 10^{-3}$ to 50 μm (fig. 1) (4). Aerosols resulting from a fire represent two different fire signatures. Particles less than 0.3 μm do not scatter light well and are classified as invisible. Those larger than 0.3 μm do scatter light and are classified as visible. The invisible aerosol signature is usually referred to as "products of combustion" and the visible aerosol signature as smoke. Invisible aerosol is the earliest appearing fire signature in most cases. Coal can evolve CO before particulates--polyvinyl cholride (PVC) materials evolve HCL quite easily.

### Energy

Fire also constantly releases energy into the environment providing some useful fire signatures. The earliest energy signatures detectable with available hardware are the infrared (IR) and ultraviolet (UV) signatures. Except for highly unsaturated hydrocarbons such as acetylene, infrared emissions from hydrocarbons are particularly strong in the 4.6-μm region due to carbon dioxide and in the 2.7-μm region due to water vapor and $CO_2$. This radiation signature can be used effectively for detection but there is the possibility of noise from manufactured IR sources. Ultraviolet fire signatures appear in flames as emissions from OH, $CO_2$, and CO in the 0.27- to 0.29-μm region.

### Gases

Many gases are added to the atmosphere during a fire that are called evolved gas signatures. A related change is the reduction of oxygen content (the oxygen depletion signature). Evolved gases may include CO, $CO_2$, HCl, HCN, HF, $H_2S$, $NH_3$, and NOx, depending on the type of material burning. The most useful gas for detection is CO, since it is present in almost all fire situations. Slow-burning and fuel-rich fires in particular produce large quantities of CO.

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[2] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

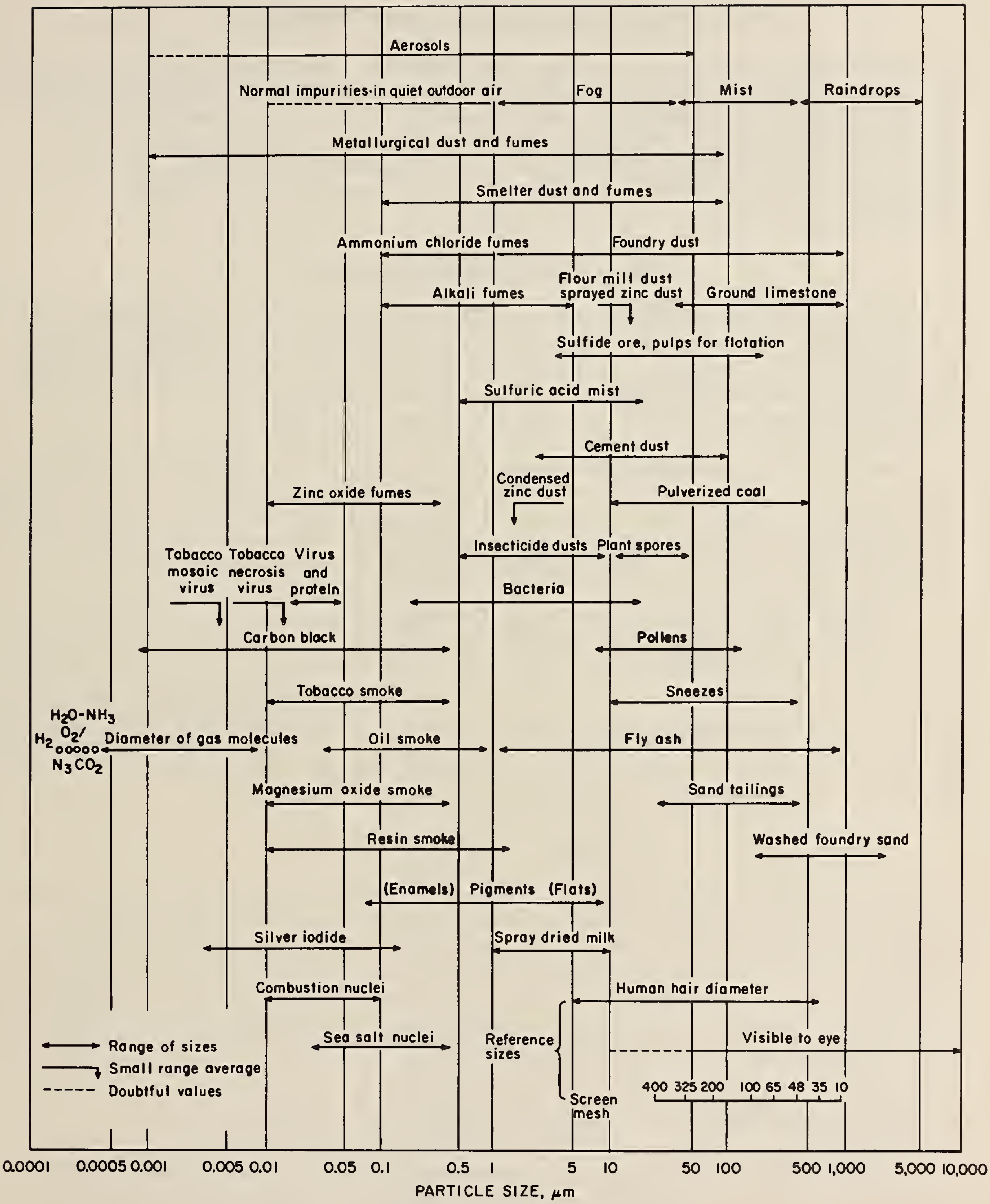


FIGURE 1. - Sizes of airborne contaminants.

## OPTICAL VIEW FIELD FLAME DETECTORS

Fire detection devices of this type respond to radiant energy portions of the electromagnetic spectrun generated during flaming combustion of materials. The principal sensing elements used include solid-state detectors--junction and bulk effects types, vacuum or gas filled tubes, and thermocouples and thermistors for special applications. The photodetector family type fills a large part of the category; table 1 gives a summary of their operating principles.

### Ultraviolet Sensing Detectors

The variety of UV detectors (wavelengths less than 0.4 μm approximately) is small compared with those in the IR region because of the basic problems associated with UV detection. Ordinary glass windows cutoff radiation below 0.3 μm and quartz and UV-grade sapphire become opaque below 0.18 μm. Below 0.1 μm there is essentially no suitable window material.

Detector Electronics Corp. (Det Tronics Corp.)[3] manufactures a basic UV detector designed to operate in the 0.18- to 0.2450-μm region. It is insensitive to both sunlight and artificial light, and has a 90° cone of vision. The quoted sensitivity is 0.093 $m^2$ flame from 4.57 m. The sensing element is a gas filled, UV-sensitive tube operating on the Geiger-Mueller principle.

Fenwal Corp. produces a UV detector responding to radiation in the range of 0.19 to 0.25 μm that also operates on the Geiger-Mueller ionization principle similar to the Det Tronics model and has a 120° cone of vision. Response time is given as 15 msec for a propane-air flame 44.5 mm high at a distance of 0.200 m from the flame source. Other suppliers include McGraw-Edison Co., and Pyrotector, Inc., with similar spectral responses and operating on the Geiger-Mueller principle. The Pyrotector device incorporates a signal delay circuit (3 sec) to minimize false alarms from sparks and lightning.

### Infrared Sensing Detectors

Infrared detectors have the problem of background radiation at ambient temperatures 86° F (25° C) being entirely in the IR region (wavelengths greater than 0.8 μm). A common method of discriminating against this background is that of chopping the incident radiant flux so that the detector receives only a fixed radiant frequency, typically 4 to 30 Hz. Combinations of optical filters and mechanical scanners have also been tried to narrow the signal wave length along with the frequency discrimination.

Infrared detectors are classified according to their method of response to heat and photon flux: thermal detectors and quantum detectors.

Thermal detectors respond to energy absorbed by a temperature-sensitive material or an absorbing film in contact with the temperature-sensitive

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[3] Reference to specific equipment, trade names, or manufacturers is made for identification only and does not imply endorsement by the Bureau of Mines.

TABLE 1. - Characteristics of different photodetector devices

| | |
|---|---|
| Photoemissive | Vacuum tubes in which light impinges on a metal cathode, releasing 1 electron per photon of light. Photomultiplier plates are often contained in the same tube envelope. Standard for sensitivity comparison. Has poor long-term stability and high quiescent power consumption, needs high voltage power supplies, and has poor shock and vibration resistance characteristics. |
| Photovoltaic | Absorbs light and produces an output voltage; does not need an external power supply. Most common materials are silicon and selenium. Selenium exhibits good response in the UV and is inexpensive; however, it exhibits hysteresis to light. Silicon photodetectors show promise in replacing selenium as cost declines. Does not exhibit serious hysteresis and has microsecond response times.<br><br>The silicon solar cell optimized for resistance to nuclear radiation (n junction on top), exhibits poor response in the UV, a broad band response in the visible, and a peak in the near IR. Silicon photocells with enhanced blue response are now available. |
| Photoconductive junction type (sometimes called photosensitive). | Conductivity changes as the device absorbs light. Reverse biasing of photovoltaic junction photocells leads to operation in the photoconductive mode. Silicon is again the most popular material for junction photoconductive cells. For reverse biasing PIN[1] processing is preferred to the conventional PN[2] junction. PIN photodiodes operated with reverse bias can have response times as fast as 1 ns. Light history effects are absent in PIN cells in either of the photovoltaic modes. |
| Bulk-effect photoconductive cells.. | Behave like resistors whose resistance decreases nonlinearly with an increase in light intensity. The usual materials are CdS and CdSe. Usually have sharp-peaked spectral responses unless they are specially compensated. Require a low voltage power supply. Major disadvantages are slow response and light hysteresis. |

[1] PIN junction is the region of transition between p-type and n-type with the diffusing process so controlled that a thin "intrinsic" region separates the n and p regions.

[2] PN junction is the region of transition between p-type and n-type material in a single semiconductor crystal.

material. Included in this category are such devices as thermocouples, metals or semiconducting layers with resistance a function of temperature (bolometers and thermistors), pyroelectric detectors whose polarization is temperature dependent, gases with pressure being temperature dependent, and thermopiles with an output of electromotive force.

Quantum detectors respond to photon flux falling on a sensing element and exciting electrons in a bound state to a free or conducting state.

Within these broad classifications the IR spectrum is divided into three divisions: near infrared (0.8 to 1.4 μm), intermediate infrared (1.4 to 7 μm), and far infrared (>7 μm). Near infrared requires conventional silicon and germanium detectors; intermediate uses special IR detectors; and far infrared calls for thermal detectors such as thermocouples, thermistors, and thermopiles. In some cases there is overlapping spectral area of response. Lead sulfide is one of the most versatile photoconductors and responds to IR from approximately 1 to 4 μm. Doping Ge with Hg and Cu extends its response to 8 to 14 μm. Sensitive areas range from 0.01 to 10 $mm^2$, with time constants shorter than 1 ns. (InSb may be more useful than PbS since it covers the CO and $CO_2$ bands but must be operated in a cooled mode, 77° K.)

Pyroelectric-type detectors are a more recent development (1,3). These consist of a slice of ferroelectric material sandwiched between electrodes to provide a sensing cell. Typical materials include triglycine sulfate, tourmaline, Rochelle salt, barium titanate, and polyvinyl flouride. Electrically, the material behaves similarly to a capacitor dielectric with a strong temperature-dependent polarization of the magnetic domains. One of the electrodes is transparent to IR radiation which causes a small temperature increase producing a polarization charge on the pyroelectric material and a corresponding voltage change across the two electrodes of the cell. Victory Engineering Corp. (VECO) manufactures commercially available pyroelectric IR detectors of triglycine fluoroberyllate and triglycine sulfate requiring no cooling, and operating at ambient temperature ranges from -10° to 60° C, and -10° to 40° C, respectively. Standard spectral response is from 1 to 45 μm.

Pyrotector, Inc., produces a near IR flame detector that responds in the spectral range of 0.65 to 0.85 μm. The detection cell is a dual element, solid-state photoresistive device with appropriate optical filters. The discrimination portion responds to wavelengths of 0.4 and 0.55 μm. The two elements function as a spectral voltage divider to detect flame and discriminate against ambient light from sunlight and incandescent or fluorescent lighting. The manufacturer quotes its sensitivity range as 6.1 m with 0.093 $m^2$ of hydrocarbon fire at 10 ft-c ambient light level (higher ambient levels decrease its sensitivity), with a 120° cone of vision. It is recommended for use in low ambient light levels such as would be found in an underground mine.

## HEAT SENSORS (DIRECT CONTACT DETECTORS)

There are two general types of heat sensors; those that employ the fixed temperature principle, and those that employ the rate-of-rise principle (10). With the fixed temperature approach an appropriate temperature level setting

is selected. When the active element is heated to its operating temperature the active element will bend, expand rapidly or maximally, fuse (change its electrical conductivity and physical state), or produce an electromotive force (emf) that can be amplified to actuate an alarm. Commercially available devices include temperature-sensitive ampoules or pellets, bimetallic elements, eutectic solders and salts, snap disks, thermocouples, and thermistors as point sensors. There is a subcategory of continuous line or wire types using thermistor material, eutectic salt, pressurized gas, or twisted insulated wires under tension. Excluding specially prepared rapid response thermocouples, a major disadvantage of these fixed temperature types of sensors is slow response time because of thermal inertia. Another disadvantage is their inability to detect low level incipient combustion in its early stages. Commercial fire detector thermocouples have response times on the order of a few tenths of a second. Advantages of direct contact detectors are low cost, reliability, and insensitivity to vibration and dust-laden atmosphere. Continuous line heat sensors have been tried in underground mines. Companies that supply this type of heat sensor are Fenwal, Walter Kidde, Protectowire, Systron-Donner, and McGraw-Edison. Their systems were developed for use in aircraft engine compartments and military vehicles and have been adapted for use in mines and mine vehicles.

The sensing element in the Fenwal system is an Inconel tube packed with a thermally sensitive eutectic salt and a nickel wire center conductor. The application of heat at any point along the element length causes the resistance of the salt to drop sharply at the eutectic temperature, causing an increased flow of current through the element. This increase in current flow is sensed by a control unit, producing an output signal to actuate an alarm. One possible problem with a eutectic salt is polarization of the material if it is used with dc voltage.

The Kidde and McGraw-Edison sensing elements contain a thermistor (semiconductor) type material whose electrical resistance drops with temperature increase. The behavior of the semiconductor material may be altered during manufacture to provide various ranges of temperature characteristics to meet different application needs. In use the cable actually performs as a temperature-averaging device, its absolute resistance being a function of its surrounding ambient temperatures. When the resistance value reaches the set point of the control system an alarm is signaled. Both the eutectic salt and the semiconductor types reset themselves upon removal of the fire condition and are rugged enough to withstand severe vibration and shock. These systems can also be connected for supervisory monitoring.

The Systron-Donner system sensing element is a small-diameter swaged tube containing a special center wire that contains an adsorbed gas. Upon heating, the gas is released and its pressure actuates a diaphragm switch attached to one end of the tube. The switch, in turn, energizes an alarm system. This system also resets itself and has supervisory monitoring capability.

The Protectowire line detector is comprised of two actuator wires individually encased in a heat-sensitive thermoplastic material. The encased wires are twisted together to impose a spring pressure between them. This assembly

is then spirally wrapped with a protective tape and finished with an outer covering to suit the environment of use. The line detector is connected in series to a suitable power supply, a supervisory relay circuit, and an end-of-line resistor, establishing a low-level monitoring current through the system. A break in the actuator, or loss of power, opens the supervisory relay, in turn producing a trouble signal from a second power source. At the operating temperature of the sensor the plastic yields to the inherent pressure allowing the actuator wires to contact each other, increasing the current flow in the system, and actuating an alarm or other function. This type of sensor does not reset itself and any portion subjected to enough heat to actuate the sensor must be removed and a new section spliced in. The lowest operating temperature available is 155° F (68.5° C), somewhat lower than the previously discussed wire sensor types, and making it ideal for mine use. The wire is resistant to moisture, chemical fumes, and other deteriorants and can be obtained in a waterproof version.

Rate-of-rise detectors are designed to respond to changes in temperature at a rate of approximately 15° F/min (8.3° C/min). They are fairly reliable and do not alarm for slow increases in ambient temperature. They are not suitable for smoldering fires and locations where rapid changes in temperature occur as part of ambient conditions.

A common way to obtain a rate-of-rise system is to use a sensor with a voltage output connected to an electronic differentiating circuit. Fenwal and the Notifier Corp. combine the fixed temperature principle with the rate-of of-rise. Two bimetallic elements with different coefficients of expansion are used. For very low rates of change both materials line up evenly and operate as a fixed temperature level device. For rapid rates of rise the materials do not expand evenly, producing an alarm even though the fixed alarm temperature is not reached.

## PRODUCTS OF COMBUSTION DETECTORS

Products of combustion in fires include solid particulates and liquid mists (including invisible and visible particle sizes), ionized species gases, and radiant energy. Combustion product detectors sense one or more of these constituents excluding heat or flame.

### Ionization-Type Detectors

Ionization-type detectors constitute one general class of POC detectors. The most common source of ionization is an alpha emitter such as $Ra_2{}^{226}SO_4$, or $Am^{241}$. Beta emitters are sometimes used but not as often since stronger sources are needed to create ionization currents similar to those produced in alpha detectors. $Kr^{85}$ is one beta emitter that is used. The radioactive emitter ionizes the air in a chamber between two electrodes. Current in the picoampere range is produced from production and transport of positive and negative ions to the opposite poles of the plates. A decrease in current, relative to clean air, is obtained when combustion products enter the chamber because the ionized combustion particles are larger and heavier than the air molecules and move more slowly toward the end of the chamber. An electronic circuit detects the drop in current and initiates the alarm.

Ionization-type detectors are also responsive to particulate matter from sources other than fires. If the sensitivity is set too high they will respond to cigarette smoke, room deodorant sprays, dust particles, and airborne particulate matter resulting from cleaning chemicals reacting with ammonia. Tests have shown that they will not react readily to certain slow-burning plastic fires producing large quantities of smoke (13). The ionization-type detector will not work properly in regions with high radiation backgrounds, and they depend on an airflow velocity adequate to cause the particulates to enter the ionization chamber but not so large as to push them through too rapidly. Chamber design is a factor here and the chamber electrodes may need periodic cleaning to remove settled dust. Most ionization-type detectors utilize the dual chamber design concept wherein one chamber detects the presence of combustion products, the other serves as a reference for sensitivity stabilization to environmental changes in temperature, humidity, and pressure.

There are many sources of ionization detectors but few of these are of an industrial quality and ruggedness to warrant testing in a mine. One of the more promising ones from the environmentally rugged standpoint is the Becon Mk II, developed and produced by the Anglo American Electronics Corp. of South Africa. It is a single ionization chamber-type, beta ray source unit developed specifically to withstand the environmental and operational conditions found in deep level gold mines. Such conditions include: corrosion, temperatures up to 104° F (40° C), air velocities up to 6 m/sec, relative humidities of 100 pct, and dust. The relatively low-cost device is also claimed to have long life, ease of installation, with little or no maintenance, and low power requirements.

The Bureau of Mines has also produced a prototype ionization fire detector suitable for mine use (8). A primary charging current of unipolar air ions is generated between two cylindrically concentric electrodes, and forced airflow through the instrument carries submicrometer particulates through the unipolar region where they acquire charge. The charged particles impinge upon a third electrode downstream, producing a current directly proportional to the particulate concentration. Two unique features of this device are a filter and cyclone assembly to protect the ionization chamber against ambient dust, and additional electrodes that provide a means of determining particulate size distribution in terms of their mobility. This unit is currently being evaluated in underground mine testing.

There are other devices or techniques that utilize the ionization effect to sense the presence of particulates or gases, but these are used in laboratory procedures and are not developed for ready use as POC detectors in a mining environment.

## Photoelectric-Type Detectors

Photoelectric fire and smoke detectors constitute another general type of POC detector. The requirements are a source of light and a detector of that light to measure its radiant power. Four different modes of operation are possible depending on the amount of light transmitted or absorbed by the medium, the amount reflected, scattered, or refracted. Most, if not all,

commercially available units possibly suitable for mine use are of the light-scattering type. A beam of light from a source travels across a light-tight chamber to a light trap or collector opposite the source. A photocell positioned at right angles to the beam senses no light as long as the air inside the chamber is clean. The chamber is open to its surrounding atmosphere through baffling, and if smoke (POC) enters the chamber, light from the beam is reflected or scattered in all directions. Some of this scattered light reaches the photocell, changing its resistance and, by suitable electronics, initiates an alarm. The alarm level is adjusted to actuate at a given smoke concentration level (normally 3.3 to 6.6 pct $m^{-1}$ or 1 to 2 pct $ft^{-1}$). In a few models the electronics is also designed to give an alarm if the rate of rise of smoke obscuration exceeds a given value (commonly 0.33 pct $m^{-1}$ $min^{-1}$ or 0.1 pct $ft^{-1}$ $min^{-1}$). Auxiliary or backup heat detection is often provided with these detectors.

Photoelectric detectors like ionization detectors may respond to particulate matter from sources other than fire. A dusty mine environment might cause some false alarms and would also require periodic cleaning of the sensor chamber internal surfaces. In a wet mine, aerosol forms of fog and mists might cause some false alarms. These detectors are also somewhat dependent on airflow velocity (good chamber design) and location because of the tendency for smoke to stratify in air streams. They are also less sensitive to black smoke compared with white or grayish smoke. Suppliers of photoelectric smoke detectors tend to be the same as those who supply the ionization types; one not mentioned previously is the Electro Signal Laboratory.

## Solid-State Detectors

Solid-state devices for the detection, and sometimes sampling of the gaseous components of products of combustion are a third general type of detector that can function as a fire detector.

A recent development in POC gas detection is the semiconductor cell detector known as the Taguchi Gas Sensor (TGS). This device uses a selection of bulk n-type metal oxides such as $SnO_2$ and $Fe_2O_3$ impregnated in a solid-state matrix material supported by conductive filaments. Variation of the formulation allows the cell to be made more sensitive to a particular gas or group of gases and insensitive to others.

A heater electrode impregnated in the cell provides sufficient increase of cell temperature above ambient to allow the cell to operate by diffusion, eliminating the need for a sampling pump arrangement. A collector electrode provides for measurement of cell conductivity, which is a function of gas concentration. The adsorption of a gas molecule on the surface of a semiconductor generally results in the transfer of electrons due to the differing energy levels of the gas molecule and the semiconductor surface. Oxygen, which can accept electrons, is adsorbed on the surface of n-type semiconductors. The transfer of electrons from the donor level of the semiconductor to the layer of adsorbed gas results in decreased conductivity of the semiconductor material.

When a TGS that has adsorbed oxygen in this manner comes into contact with reducible or combustible gases such as CO, hydrocarbons, etc., the molecules of these gases are adsorbed and the transfer of electrons is in the opposite direction to the oxygen reaction, releasing the electrons to the semiconductor space charge layer and causing a large increase in the conductivity of the sensor. The sensor output is sufficiently large to allow gas detectors to be designed using a minimum number of components, allowing the production of low-cost detectors.

Significant advantages of these solid-state electrolytic cells are the very long life times expected, usually several years, the low cost and simplicity inherent in its design, and the relatively simplified electronics needed to utilize the sensor output. Other features include not being permanently poisoned by the toxic gases, resistant to vibration and shock, and having no loss of sensitivity even at gas concentrations so high that air (oxygen) is displaced.

A severe disadvantage is its ease of alarming in areas containing engine combustion products, and its sensitivity to a wide variety of easily oxidized gases not necessarily associated with products of combustion.

For fire detection use the TGS responds readily to CO which is one of the principal gases given off in the early stages of fire. However, because of its sensitivity to gases other than POC and exhaust gases, its practical use may be limited to a hybrid system involving ionization or photoelectric detectors. TGS detectors can be calibrated within the range 200 to 1,000 ppm CO and to a limited extent can be made selective to CO.

## Electrochemical Detectors

Electrochemical (fuel cell) techniques for CO sensing are available commercially from, among others, Energetics Science, Inc., in their CO Ecolyzer, Mine Safety Appliance Co., and from Interscan Corp. These devices depend on the electrochemical reaction of the detected gas, oxidized or reduced (depending on the sensor) at an appropriate electrode potential, producing an electric current which, under membrane diffusion controlled conditions, is directly proportional to the gas concentration. These devices are subject to interference from gases other than that desired for detection, but are capable of precision calibration making them useful as an analytical device.

Recently, compact, portable, and fairly rugged models of electrochemical detector systems have come on the market. Some have Mining Health and Safety Administration (MSHA) approval for hazardous area use. There has not yet been time to thoroughly evaluate and test these models in in situ mine situations over extended periods of time and use.

## Optical Gas Detectors

Optical gas sensors are generally confined to laboratory use, although recent prototype models have been developed for personnel hazard monitoring. These use the strong adsorption band of CO at 4.65 μm (infrared). Radiation

from an infrared source is passed through a cell through which the sample gas flows and is adsorbed by the CO molecule. A filtered infrared detector responds to this change in radiation and its output is compared with a reference cell, conditioned by suitable electronics and read out on an appropriately marked meter.

A technique useful with different POC detectors is the use of tube bundles (7). With these, air samples can be drawn from different sections of the mine and sequentially monitored at a central location. This procedure provides protection and stability for the detector systems and can add to the flexibility of the mine fire protection system. Slow response times and wall-diffusion losses for submicrometer particles are undesirable features of these systems.

## ENVIRONMENTAL CONSIDERATIONS

Metal and nonmetal mine environmental extremes can include temperatures below 0° to 100° F (-17.8° to 37.8° C) or higher, dry air to 100 pct relative humidity, high air velocities--sometimes up to 40 miles/hr (24 km/hr) in ventilation air intakes, and pressure drops of up to 12 inches (30.5 cm) of water across pressure doors. Added to these can be diesel exhaust fumes, shot firing gases, and normal mine gases. There are two environmental problems to be faced in designing a reliable fire detection system: Will it continue to operate, and if it does, can it discriminate against the normal mine ambient parameters.

The latter problem can possibly be dealt with by the use of combinations of detector types in the system to provide detection of cellulosic and hydrocarbon fires, spontaneous combustion, and electrical fires. Ambient parameters will differ in various parts of the mine. Occasionally air ventilation networks can improve a POC detector's sensitivity and effectiveness. Sampling tube networks or remote detectors with telemetry can monitor several locations individually. A detector type useful in one location may be quite unsuitable for use in another location; therefore, if conditions change with time, the sensor system should be reevaluated.

There is no universally applicable fire and smoke detector that responds equally well and consistently to all types of fires. The various detector types have been discussed along with some to their advantages and disadvantages. Long-term evaluation of the various detectors' sensitivity and reliability under the extremes of ambient conditions just described are underway and will lead to viable, cost effective detection and suppression systems for underground mine fires. Until such systems have been developed, and environmentally and operationally reliable detectors of various types made available through long-term testing, it is best that unreliable fire detectors not be installed in mines.

Ability to discriminate against normal mine ambient parameters is an important consideration in the design of reliable fire detection systems. Mine Safety Appliances Research Corp. (MSAR), under a Bureau of Mines contract (11), provided CO, $CO_2$, $NO_x$, and NO concentration data for shot firing and diesel operations in selected mines and sampling sites within the mine.

Table 2 taken from their report, summarizes much of their data in the form of ratios of contaminants measured in connection with various mine operations. The report suggests that a dual sensing system involving contaminant ratios may provide an approach to minimizing or eliminating false alarms. The $CO/CO_2$ ratio of diesel exhaust is quite comparable to that of the combustion products of a metal mine fire. Similarly, the $CO/NO_x$ ratio for shot firing and a leaking bulkhead, where a hot spot was thought to exist, are also quite similar. The $CO_2/NO_x$ ratio is significantly different for shot firing and diesel operations compared to the ratio for a fire and/or the leaky bulkhead with a hot spot. This much higher last ratio may provide a reliable means of fire detection. The report also suggests that studies of the time-distance behavior of the $NO/NO_x$ ratio be made if the $CO_2/NO_x$ ratio were to be employed as a means of incipient fire detection.

TABLE 2. - Average contaminate ratios for various underground activities

| Activity | $CO/CO_2$ | $CO/NO_x$ | $CO_2/NO_x$ |
|---|---|---|---|
| Shot firing.................. | 0.38(0.44) | 6.35(4.58) | 11.6(12.4) |
| Diesel....................... | .04 | 6.9 | 97 |
| Fire......................... | .025 | 100 | 4,000 |
| Leaking bulkhead, 4,200 feet.. | .03 | - | - |
| Leaking bulkhead, 3,600 feet.. | .001 | 12 | 8,000 |

Source: Mine Safety Appliances Research Corp.

In an early Bureau contract study by the Gillette Research Institute (14), two different types of battery powered ionization detectors were taken underground for a short-term performance evaluation. One, taken into the Bunker Hill mine, Kellogg, Idaho, performed poorly after a few hours of operation in areas contaminated with high concentrations of aerosols and in regions of high ventilation airflows. It did operate satisfactorily in regions supplied by low-velocity intake air.

The other detector, a dual-gate type, performed reliably at Central Rock Co., Lexington, Ky. The latter device was not necessarily superior to the former because the Bunker Hill mine presented far greater extremes of environment. What the experiment tended to demonstrate was that state-of-the-art ionization sensors, developed for normal industrial or residential use, military or commercial aviation fire protection have questionable reliability or, in this case, are inappropriate for use in a mine environment.

Detector manufacturing companies say that improper maintenance is an important contributing factor to the high mechanical and electrical failure rate of detectors. On the other hand, recommended cleaning procedures such as dust or adsorbed combustion products removal from electrode plates of ionization detectors by way of disassembling the detector head or installing a new detector and cleaning the used one aboveground will cause a heavy burden on effective maintenance in environmentally extreme regions of the mine.

These problems, along with those mentioned previously in the discussion of POC-type ionization detectors, might lead one to see limited applicability for the ionization detector in the mine environment. Yet, by contrast, the Becon Mark II ionization detector, also described previously, shows promise of long-term reliability both environmentally and operationally. It is currently under long-term testing and evaluation. Disadvantages of the Becon Mark II are the need for Nuclear Regulatory Commission licensing, because of its high beta ionization level, and the need to import it. Domestic models with comparable features are under development and show promise of being equally effective.

Another important consideration involving mine environment is the spacing and positioning of fire and smoke detectors in the mine. Little is known about optimum detector positioning and spacing in mines. NFPA installation standards do not offer any criteria directly useful in a mine since their codes deal with residential and commercial situations. Mines vary so widely in distribution of combustibles, ventilation patterns, and roof support systems that an installation type code would not be feasible. Complicated ventilation patterns, random ceiling obstructions, and a variety of tunnel shapes would not allow general applicability of such a code.

Areas in the mine that represent high risks to personnel and property would require increased numbers of detectors per given area. High risk areas include fuel storage depots, regions at or near shafts, and abandoned or worked-out areas containing combustibles that might ignite spontaneously.

Direct contact thermal detectors are highly reliable but in some cases may not respond rapidly enough. In a fuel storage area, for example, a fire could quickly develop to an advanced stage before actuating the extinguishing system if only direct contact detectors were used (fig. 2). In this situation a flaming fire would likely propagate rapidly, thus calling for a detection-actuating system using fast responding optical flame sensors.

Protection for an underground storage area for other than class B materials storage would require a different combination of sensors. In such an area, combustibles such as wood timbers and lagging, ventilation ducts, rags, cartons, conveyor belts, tires, wood structures, and oxygen-acetylene tanks might be found. The normal mine environment, in or near a storage area, could produce stimuli that would falsely trigger the different types of fire and smoke detectors. Smoking, diesel-powered equipment exhaust, dust, certain types of lights, blasting agent residues, high air velocities, and welding and cutting gaseous products are examples of contaminants in the normal mine environment. An alarm system utilizing smoke detectors to provide early warning and a backup system utilizing a thermal wire sensor might be useful in this case.

As previously noted, thermal wire sensors are very reliable and rugged but might allow a fire to develop to a fairly advanced stage before signaling. With the combustibles mentioned above, a slow, smouldering fire could develop and exist for sometime without producing high heat. A smoke detector would give an early alarm and would signal personnel in the area or on the surface

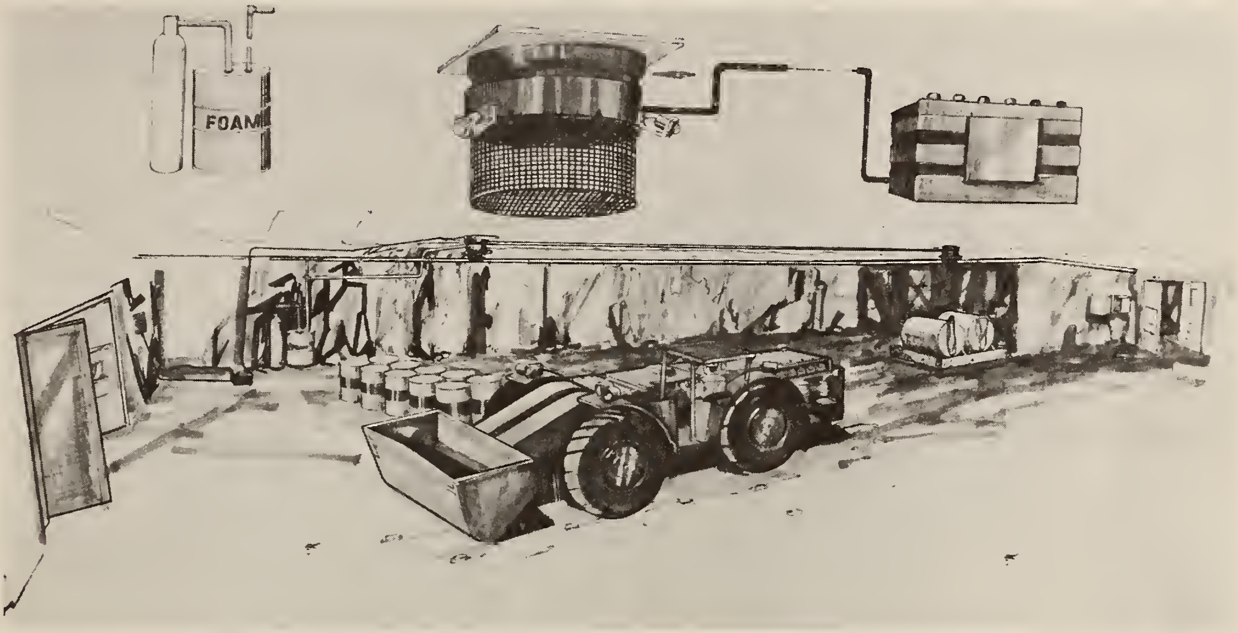


FIGURE 2. - Conceptual fuel storage area prototype fire detection-suppression systems.

to investigate and take appropriate action. The smoke detector should not actuate the extinguishing system automatically because this type of detector sometimes alarms in the presence of welding activities, diesel exhaust, or excessive dust. The extinguishing system could be heat activated, either intrinsically or by the thermal wire sensor; the latter giving an alarm to personnel in the area or on the surface. The two types of sensors, connected to different audible and visual devices, alarming together would indicate a true fire situation.

A third situation might call for protecting an underground maintenance shop area (fig. 3). Similar combustibles would be found in a shop area as are found in a storage area with the likely addition of motor oil, hydraulic fluid, and lubricants and their spillage residues. Volatiles such as paints and rubber or plastic materials are likely to be found there. In addition to these possible sources of false fire alarming, cleaning fluids and higher concentrations of diesel exhaust are likely to be present.

A dual sensing and extinguishing system of a slightly different type might be useful in this area. Thermal wire sensors would provide automatic actuation of fire extinguishing equipment and zone isolation as before, and a CO detector would provide early warning of fire. The CO detector, possibly a TGS type, adjusted to alarm at 50 to 100 ppm would provide a dual service. TGS-type sensors are also sensitive to hydrocarbons and will alarm in the presence of excessive levels of cleaning solvent vapors as well as CO from diesel exhaust, thus providing some protective warning from an air pollution standpoint.

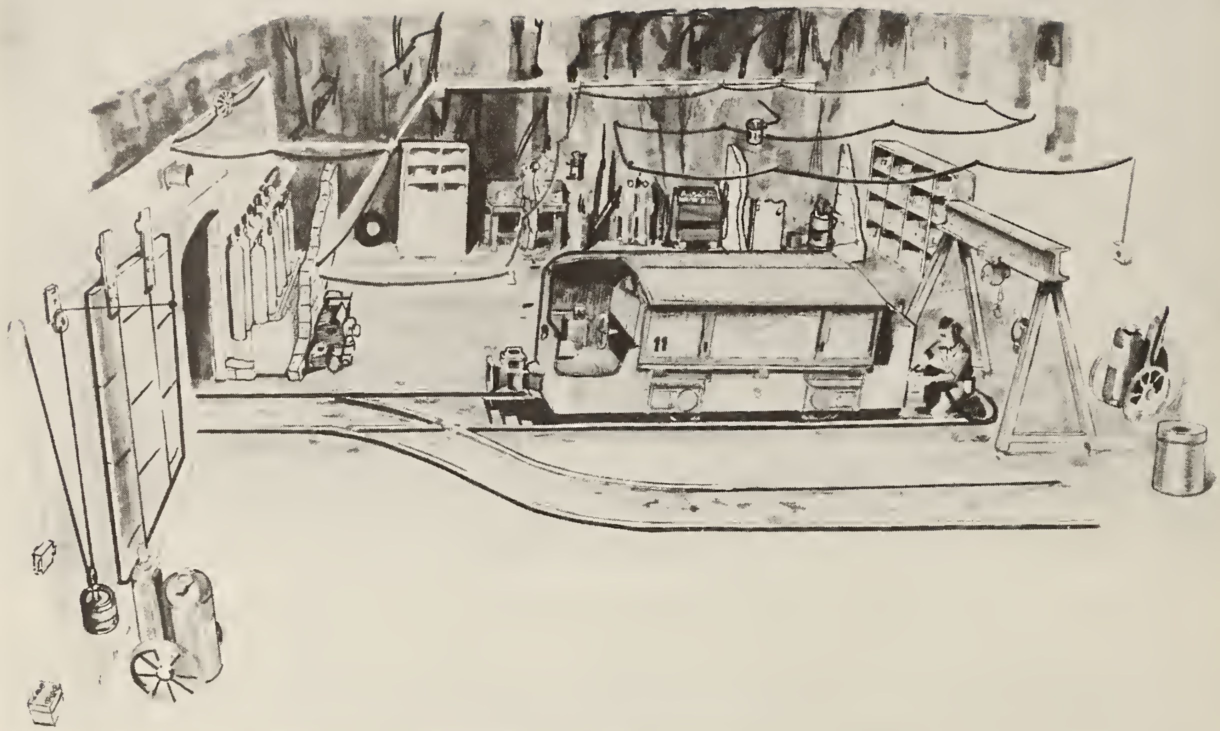

FIGURE 3. - Conceptual underground maintenance shop prototype fire detection-suppression system.

Because of the fuel-to-air ratio influence, a knowledge of the relationship between fire and mine ventilation is essential for the proper selection and location of sensors and detectors and also for the correct interpretation of information provided by them. Mine fires can be categorized into two distinct types--oxygen rich (overventilated), or fuel rich (underventilated). The fuel-to-air ratio determines which type occurs; the oxygen-rich type can evolve into the fuel-rich type by spontaneous growth. Timber fires (fuel-rich) represent an extreme toxicity hazard because of low $O_2$ concentrations and high CO and $CO_2$ concentrations. Fuel-rich conditions also produce more smoke, increasing toxic species exposure,and obscured vision.

The greatest hazards of mine fires are caused by toxic and sometimes explosive products of combustion being carried through the mine by the ventilation system and unexpected airflow reversals carrying toxic fumes to intake air ventilation areas, such as fire escape routes, hoist areas, and other areas usually thought of as safe in the event of a fire. The analytical prediction of airflow reversal in a mine, even under ideal conditions, is a very difficult task and beyond the scope of this report. However, Greuer (6) has compiled a large number of references and provided a detailed accounting of the influence of mine fires on the ventilation of underground mines for those who wish to pursue the problem in detail.

Greuer (6) makes a few quantitative predictions of ventilation disturbances that may be useful in interpreting the indications seen when monitoring a fire detection system that includes the following:

1. Throttling and natural draft changes can cause changes in the quantity of ventilating air currents and sometimes a reversal of their direction. Similar changes can occur in neighboring connected airways as well as that of the fire scene.

2. Air (oxygen) quantity reductions ($O_2$ pct) in nongassy mines can be neglected. In gassy mines air reductions can lead to explosive mixtures that may be carried back through the fire zone.

3. Ventilation disturbances can also cause smoke layering which may affect the ability of a detector to operate effectively.

## BUREAU OF MINES EXPERIENCE

### Shaft Installations

To work towards an answer to the major problem of fire hazard and contaminated air resulting from fire, the Federal Bureau of Mines contracted with the FMC Corp., San Jose, Calif., to evaluate mine shaft fires and their hazards. (5). The contract also called for the development and demonstration of a low cost, reliable mine shaft fire protection system that could be adapted to a majority of metal and nonmetal mine shafts, raises, and winzes, especially in deep mines. Results of this contract have been published elsewhere (5) so need not be detailed here. However, as an example of a proven system, sensor and detector components that performed successfully in underground tests with controlled fires will be highlighted here.

As part of the background preparation for designing the systems produced, it was found that approximately 67 pct of shafts in metal and nonmetal mines are of wooden construction, and contaminated air was responsible for about 77 pct of fatalities from fires. Causes of fires in mines were predominantly electrical (35 pct) and welding (18 pct). Most fire-connected fatalities occurred in or near shaft stations, the gathering point to normally leave the mine.

Four major needs were brought out for providing effective mine fire and smoke protection:

1. Reliable sensors are necessary for early fire and smoke warning.

2. Isolation barriers (vent doors) would stop the flow of contaminated air.

3. Available water supplies could assist with fire extinguishing.

4. Recording sensor systems and control of ventilation doors and extinguishing systems from the surface would be preferable to sending firefighting teams underground.

The possibility of a fire starting somewhere in the mine is always present because combustibles and ignition sources are always close together. In addition to constant fire-prevention efforts, provisions should be made to detect and extinguish fires as soon as possible. Sensors and detectors are needed because fires can occur spontaneously in abandoned workings or accidently in unattended areas, and depending on detection by persons working in or passing through an area is not realistic.

Besides simply detecting a fire, provision should be made to alert an attended area that fire exists and its location, to alert people underground that a fire has been observed or reported, to take some action to isolate the fire area, and to extinguish the fire if possible. Meeting these requirements was possible with existing equipment integrated into a functional protective system consisting of sensors, extinguishing agents, isolation barriers, and appropriate controls.

The harsh environmental conditions that exist underground have already been mentioned. Because labor and maintenance efforts are at a premium underground, all components used in this detection-alarm system must be extremely rugged to limit repair needs or they may be out of service at just the wrong times, and they must be reliable to instill confidence in their ability to perform and alarm only in a fire situation.

The first prototype mine shaft fire and smoke protection system was tested at an inactive silver mine in the Couer D'Alene district of Idaho. The system was installed 3,000 feet below the shaft collar to protect 50 feet of shaft, the shaft station, and 100 feet of drift in two directions.

Environmental conditions in the mine were 100° F and essentially 100 pct humidity. Because the mine was inactive, there was little or no dust present during the 2-week test period. Ventilation was not typical of that found in a working mine either because the mine was used exclusively for ventilation and as an alternate escape route for an adjoining working mine. Airflow was temporarily modified for the test.

The sensors installed included thermal wire, CO gas, and ionization types. The thermal wire provided backup reliability for the other two early warning types. Carbon monoxide gas and ionization sensors were placed in sections of the shaft and shaft station areas. A pair of each was placed near the shaft crown plate to sense air entering the area, which was downcast intake air. Others were located near the ventilation barriers towards the mine workings (away from the shaft station area).

Sensors were selected to respond to health hazard levels of fire or contamination by fire (gas-smoke), while being available off-the-shelf, reasonably priced, and compatible with metal-nonmetal mine environments as previously described. Sensors are pictured in figure 4, and consist of smoke (ionization) detectors, Becon Mark II, manufactured by Anglo American Electronics, Republic of South Africa; two carbon monoxide (gas) sensors, model CO-181 manufactured by Dynamiation Enterprises, Inc., Ann Arbor, Mich.; and model MSD-1 manufactured by Enmet Co., Ann Arbor, Mich.; and thermal wire, type WPP, 155° F manufactured by the Protectowire Co.


FIGURE 4. - Smoke (*A*), gas (*B*), and heat (*C*) sensors.

The ionization detectors are referred to as smoke detectors in the system even though they primarily sense invisible submicrometer particles (as distinguished from the second detector type, labeled CO, which responds to CO and other components of smoke).

During extensive factory tests, the ionization detectors performed well. They consistently detected wood fire smoke within habitable levels. Test data indicate the detectors alarmed at smoke density levels of 2 to 6 pct obscuration per foot. This compares favorably with industry standard set points for commercial and residential smoke detectors. A poor response to plastic produced smokes appears to be characteristic of ionization-type detectors, and the Becon unit is no exception. However, the Becon unit is designed for mine environments and does not readily exhibit problems from corrosive environments, dust, humidity, and very high air velocities.

The CO detectors in the system use the Taguchi gas sensor (TGS). They were used at factory settings of 200 ppm CO on the Enmet unit and 75 ppm CO on the Dynamation units. These levels were felt to be realistic for the conditions expected in the test shaft. There was no blasting or diesel equipment operating to increase the CO level at the demonstration site. On the other hand, a CO concentration of 150 ppm may be encountered with some regularity in

active mines where blasting and diesel equipment are present. A level of 150 ppm is tolerable without hazard for up to 3 hours, thus setting alarm points of CO monitors above 150 ppm would represent a realistic alarm level within the limits of safe habitation for short periods, but an extended 200 ppm concentration could be a valid indication of a fire, especially if combined with other indications.

A surface control unit was installed in the hoist room and connected to an underground control unit in the shaft station at the 3,000-foot level. The latter was the junction point of the sensors and related components and provided the interface between them and the surface control unit. The two control units were connected by a single pair of wires with a second pair for redundancy. Multiplexing the signals allowed the surface control unit to handle 16 inputs from the underground control and process 8 outputs for transmittal back to the underground unit.

A fire fueled by wood cribbing was built in a steel pan 3 feet square, about 18 inches deep, with a lid that was raised and lowered to adjust smoke density and products of combustion.

Smoke and CO sensors responded to contaminants in the fire area, all system commands were remotely operated from the surface control unit and performed as designed. The fire was extinguished by the installed sprinkler system during a 6-minute discharge. The thermal wire was located too high above the controlled pan fire to reach its alarm temperature and did not respond.

The first prototype system was installed for only 2 weeks in the Idaho mine which did not test the long-term reliability of the system and components. A second system was installed in Union Carbide Corp.'s Pine Creek mine in Bishop, Calif., where it could be given a larger test.

Several modifications were made to adapt the system to the particular mine location and it was installed and continuous monitoring began on December 19, 1975. A second prototype system based on recommendations derived from developing, installing, and monitoring the first prototype, was built and installed at a second level in the Pine Creek mine as an add-on-unit to the first prototype using the same interconnecting wires. The latter system included a new microprocessor controlled surface unit, replacing the original prototype surface unit. System testing was concluded in July after controlled fire test demonstrations were performed in each of the two underground areas. Final results include 3 months operation of the first prototype system, providing 87 days of 24-hour-per-day monitoring. The second prototype system was installed 3-1/2 months, providing a combined total of 105 additional days of monitoring for both levels.

The surface control unit was installed on the surface at a guardhouse where it was monitored 24 hours per day. The fire and smoke protection systems were placed at two locations deep within the mine--one in a large compressor station 14,000 feet in the mine at the 9,400-foot level, and the second 14,000 feet in the mine at a shaft and shaft station area at the 11,271-foot level. Because the mine is inverted, deeper operations are at higher elevations.

Three types of sensors were used at each of the two test sites as in the initial test setup. Thermal wire was strung throughout the drift and machinery space of the compressor station and around and down the shaft at the 11,271-foot level.

Ionization and CO sensors were used in pairs except none of the CO sensors were used in the compressor room. An ionization sensor was located above the compressor machinery, one located on each side away from the compressor station, in intake air, beyond remotely controlled vent doors, and one in the upcast exhaust airflow from the shaft at the 11,271-foot level. An additional ionization sensor was placed in the diesel maintenance area, three fans were monitored, one was controlled, and air lock doors were monitored.

During the monitoring period, the smoke (ionization) detector in the diesel maintenance bay regularly alarmed during vehicle activity, requiring an adjustment of its sensitivity. Also the smoke detector in the compressor station was readjusted because of alarms. The sensors responded to various known mine activities--diesel exhaust, blasting, and gas and electric welding and cutting vapors.

After the monitoring period each location was subjected to a test fire using a pan and cribs identical to those used in the Silver Summit test. At the 11,271-foot level it was allowed to burn for nearly 12 minutes before the surface control unit was used to turn on the installed sprinkler system. During the fire the sensors detected over 100 ppm gas and smoke buildup, and alerted surface personnel that they were in alarm. All alarming and control functions performed satisfactorily through the surface control unit operated by surface personnel.

At the 9,400-foot level, a similar fire was allowed to burn for 13 minutes before the surface control unit turned on the sprinkler system. Again, alarm and control functions operated satisfactorily through the surface control unit, responding to the buildup of smoke.

## Underground Fueling Area Installation

A prototype underground fueling area system was designed, tested, and is now undergoing long-term testing at an underground fueling and storage area of the Union Carbide Corp.'s Pine Creek Mine. This was developed and installed under a contract to the Ansul Co., Marinette, Wis. (2), to develop safe practice guidelines that minimize the chances of fire in underground fueling areas and to develop a low-cost, reliable, automatic fire protection system for underground fueling areas.

The detection and control subsystem contains two ultraviolet-type detectors monitored by a control panel that provides a pneumatic output to the suppression subsystem when flames are present within the cone of vision of the detectors. The detectors are self-contained units that accept 24 vdc and provide both instantaneous and time-delayed form C contacts as outputs. The control system uses the 5-second delay contacts as a zone alarm input. The detectors respond to ultraviolet and include an optical integrity feature

that allows remote testing of their optical lenses. The detectors are housed in explosion-proof enclosures and placed in the fueling area such that their 90° fields of vision overlap and each covers the complete area.

The two detectors are cross-zoned within the control unit to minimize false alarms. This means that both detectors must sense the fire before the fire signal passes to the actuation device. The fire signal operates a mechanical releasing device that releases an internally stored pressurized gas to operate the suppression system. The control unit has an internal, adjustable time delay to delay actuation of the suppression system at a predetermined time after the alarm signal is received. This allows the use of an "abort" function through the control unit to prevent system discharge in the event of a false, or nuisance alarm, and also allows the use of predischarge alarms. The control unit has additional relay contacts to allow for external ancillary functions and remote annunciation: however, the prototype system includes only local alarms.

The control unit is powered directly from an emergency power source which converts primary ac power to low-voltage dc power for the control unit and also maintains a float-charged secondary standby battery source. The standby batteries have sufficient energy storage capacity to operate the entire system for a period of at least 24 hours.

The total system was tested on a component basis as well as on a system basis before installation in the mine. A field demonstration was performed at the mine.

Underground installation of the detection and control subsystem was completed first and detector performance was monitored for several days before the demonstration. During 3 days of monitoring, no false alarms or other problems occurred. On the fourth day, a malfunction was discovered in the unused portion of the time-delay circuit that was caused by the temperature-humidity effect of the underground atmosphere. A new circuit board was installed in that portion of the subsystem.

On July 31, 1977, two underground fire tests were performed to determine the discharge characteristics of the system and to check the coverage of the fire suppressant. These were entirely satisfactory and follow-on, long-term validation testing of the prototype hardware has continued at Pine Creek mine. During the past nearly 20 months of in-mine testing, there have been no functional failures of the system, although the detector lenses have required an occasional cleaning.

## Additional Underground Tests

Responses to fires from different fuels, nonfire stimuli, effects of air velocity variations, dust buildup, and effects of mine environments are of interest over long-term testing.

Therefore, the Bureau's Twin Cities Mining Research Center entered into a purchase contract with the FMC Corp. to obtain a sensor package suitable for

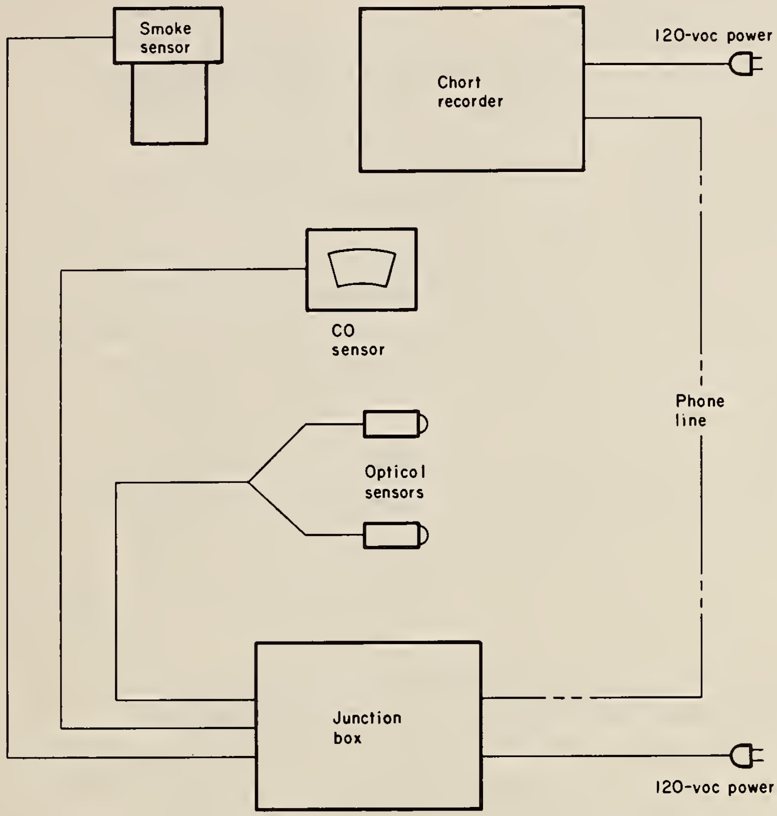


FIGURE 5. - Underground metal mine fire sensor package diagram.

long-term, in-mine testing. A cooperative agreement for locating and testing the package was also negotiated with the Hecla Mining Co., Lakeshore mine near Casa Grande, Ariz.

A three-sensor package containing a Becon Mark II smoke sensor, an Enmet ISA-33 CO gas sensor, and two Pyrotector 30-2013-9 flame detectors were assembled (fig. 5). An additional CO gas sensor (Dynamation CO 181) was supplied for additional testing at a different location in the mine.

The three-sensor package was installed in the underground diesel fuel storage area located at the end of the 500 east exhaust crosscut. The single CO gas sensor was installed in the south decline near the mine's existing Ecolyzer gas sensor. Each sensor was connected by telephone wire pairs to a nine-channel recorder on the surface. These packages were installed in late March 1976, and have been undergoing long-term testing.

Periodic visits to the mine to observe the sensors indicated some problems. The interface electronics and the CO sensors are packaged in NEMA IV electrical enclosures and well-protected from the mine environment. The TGS sensors that are part of the CO monitors are not stable in that their base level output drifts over time and with temperature variations. They are also quite sensitive to diesel exhaust emissions and blasting residue gases in the mine.

The flame detectors remained operational but they became dust covered with time since they are in an exhaust crosscut where the air velocity is quite high and dusty.

The smoke sensor remained operational but after several months was not alarming as it should. Blowing accumulated dust away from its baffle entrances caused it to go into alarm, and it could be made to alarm by checking its trigger level adjustment. Dust accumulated in the baffle area in this location to the extent it needed to be cleaned out every few months. The alarm level was adjusted later so it would not respond to the exhaust fumes from standing, idling load-haul-dumps in the passageway to the fueling areas. Additional long-term testing of sensors will be continued in mines with differing environmental conditions.

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